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# ADJUSTMENT AND VALIDATION OF THE MATHEMATICAL PREDICTION MODEL FOR SWEAT RATE, HEART RATE AND BODY TEMPERATURE UNDER OUTDOOR CONDITIONS

ANNUAL REPORT


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~~The present~~ study is conducted in order to validate under outdoor conditions, and if necessary, to adjust the mathematical models, which were developed in USARIEM, to predict physiological tolerance under different environmental conditions. Twenty male subjects were exposed to different combinations of climatic conditions, solar loads, clothing ensembles, and metabolic rates. Different physiological parameters were carefully monitored. The results show that the prediction models, which were developed from laboratory studies, are conservative and overestimate the physiological responses under outdoor conditions. It is hypothesized that a factor related to long waves radiations should be included in the equations. This issue will be investigated during the next phase of the study.

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## SUMMARY


During the last two decades the Military Ergonomics Division of the U.S. Army Research Institute of Environmental Medicine have developed a series of predictive equations for physiological responses of clothed soldiers performing physical work in various environmental extremes. However, these predicting models were developed under controlled laboratory conditions. The present study is undertaken to validate these predicting models under outdoor conditions. Twenty fit subjects were exposed to 12 combinations of climate, clothing and metabolic rates. During the experimental sessions physiological and meteorological parameters were collected. The data obtained for rectal temperature and sweat rate was compared with the predicted values. It was observed that under the outdoor conditions the indoor predicting models for rectal temperature and sweat loss overestimate the outdoor actual values. It has been concluded to continue the study in an attempt to investigate the outdoor factor which cause a deviation from the predicted values.

## FOREWORD

The objectives of this grant are: a) to evaluate the physiological responses to physical activities at various metabolic levels, performed under different outdoor conditions when different clothing combinations are applied; b) adjust the mathematical models which were developed in USARIEM to predict rectal temperature and sweat rate production for natural outdoor conditions.

The mathematical models for the prediction of rectal temperature and sweat production were developed and assessed under controlled laboratory conditions. The present study is based on the hypothesis that, they will be valid for outdoor conditions with only minor modifications and adjustments.

For the protection of human subjects the investigators have adhered to policies of applicable Federal Law 45CFR46.

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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## INTRODUCTION

Three major physiological factors determine the ability of men to tolerate heat while operating under hot climate: body temperature, cardiovascular adjustments and water balance. During the last two decades mathematical models for predicting body temperature, heart rate and sweat rate response to a given heat load, have been developed (1-6). These models have been validated for numerous combinations of environmental conditions, physical activity and clothing, all under controlled laboratory conditions.

Thermoregulatory balance of the body is determined by the relation between the evaporative cooling required ($E_{req}$) and the maximal evaporative heat loss to the environment ($E_{max}$). Sweat loss is expressed by the same terms:

$$m_{sw} = 27.9\ E_{req}\ E_{max}^{-0.455}\ ;\ (g\ m^{-2}\ h^{-1})$$

$E_{req}$ is constituted of the metabolic heat production, heat transfer characteristics of clothing, and ambient climate conditions; $E_{max}$ is dictated by the vapor transfer properties of clothing and the vapor pressure gradient between the skin and the air. In a similar way $T_r$ and HR are predicted.

Solar radiation which has an additive effect on the thermoregulatory balance is not taken into consideration in these equations. Thus, these models are effective and acccurate for indoor conditions, but not necessarily so for outdoor climate. Recent preliminary experiments, using artificial indoor solar radiation by infrared electrical lamps, suggest that the radiant heat load $H_{(r)}$ should be added to the physical heat exchanged between the body and the environment ($E_{(R+C)}$) when the mathematical formula for sweat rate prediction is applied. According to this modification $H_{(r)} = K$ (MRT) when: K is a coefficient which depends on the ratio direct to diffused radiation and on clothing, and MRT is the additive value to mean radiant temperature of solar radiation. MRT can be expressed also as:

$$MRT = (1 + 2.2\ V^{0.5})\ (T_g - T_a); \qquad (^oC)$$

Where $T_g$ is the black globe temperature and $T_a$ is the ambient temperature.

In order to apply the predicting models for outdoor conditions, field research was designed.

## MATHERIAL AND METHODS

The first stage of the study was conducted during the summer of 1986, under natural climatic conditions of a desert (hot/dry) and coastal (hot/wet) areas of Israel.

Subjects. Twenty fit male volunteers, 17-19 years old participated in the study after being briefed by a senior investigator and signing an informed consent form. The subjects were inhabitants of either the desert or the coastal region, naturally acclimatized to the local climatic conditions.

Preliminary Screening. Prior to experimental testing each subject underwent medical examination including resting E.C.G., urinalysis and SMA-12 screening chemistry. To determine aerobic power, oxygen uptake at maximal exercise was analyzed using a computerized metabolic chart (MMC-Horizon; Sensor Medics). A progressive treadmill running test was performed at a constant speed of 8 mph and a stepwise grade increment of 2% every 2 min. until exhausion. The test was conducted indoors under comfort thermal conditions ( 20 $^{o}$C; 50% relative humidity).

Experimental Design. Two groups of 10 subjects each, were exposed to either hot/dry (desert) or hot/wet (coast) climate. Each subject in either group participated in 12 experimental sessions, assigned to him at random. All experimental sessions were carried out between 11:30-13:30. The experimental combinations were as follows:

1. Solar radition: Sun (maximal solar radiation)
   Shade (minimal solar radiation)
2. Clothing: Standard fatigues
   CB protective overgarments (MOPP IV)
3. Metabolic rate: Rest ( 100 watt)
   Moderate work ( 320 watts)
   Heavy work ( 425 watts)

Exercise consisted of treadmill walking at speeds of 4.8 km $h^{-1}$ and 7.2 km $h^{-1}$ to elicit the desired average metabolic rate. Each experimental session lasted 120 min., consisted of two bouts of 10 min. of rest and 50 min. of exercise.

Physiological Status Assessment. Prior to exposure and at 5 min. intervals during the test until its end, heart rate and rectal temperature were monitored. Skin temperature was monitored at 15 min intervals. Rectal temperature was recorded with a

Yellow Spring Instrument (YSI) rectal termistor probe inserted 10 cm beyond the anal sphincter. Skin temperature was monitored with a YSI skin termistor. Skin temperature was measured simultanously at 3 locations (chest, calf and forearm). Weighted skin temperature ($T_{sk}$) was calculated according to Burton (7). Oxygen consumption was measured during the rest and exercise periods using an automated metabolic chart (MMC-Horizon, Sensor Medics). E.C.G. electrodes were affixed to the subjects chest (CM-5 placement) and heart rate was recorded parallel to the metabolic measurement. Body weight was measured with an electronic scale (accurate to $\pm$10 g). Ad libitum drinking was encouraged. Water intake and urine output were precisely measured. Sweat rate was determined from weight loss (by measuring the subjects weight pre and post exposure) adjusted for water intake and urine output.

Meteorological Parameters. During the experimental sessions the following environmental variables were continuously monitored:

1. dry bulb temperature, with a sling psychrometer.
2. wet bulb temperature, with a sling psychrometer.
3. wind speed, with a cap anamometer.
4. black globe temperature, with a 6" copper globe.
5. solar radiation, direct radiation and infrared radiation with a Spectral Pyranometer (model PSP, EPLAB U.S.A.).

Calculations. The actual results were compared to the pedicted values using the mathematical models as summarized by Pandolf et al. (8).

## RESULTS

The mean ambient temperature in the desert area was slightly higher than that of the coastal region ($32^{o}C$ and $30^{o}C$, respectively). Solar radiation was also similar in both regions ($800$ watt $m^{-2}$). However, relative humidity was about 15% higher in the coastal area than in the desert area (60% and 45%, respectively).

Tables 1 and 2 present the mean rectal temperature after 60 and 120 min. of exposure to ambient climate at the coastal (Table 1) and desert (Table 2) areas. The data is presented in comparison to the predicted values. Table 3 presents the results concerning sweat loss (presented as $g\ h^{-1}$) under the different combinations both for the desert and coastal areas. Consistently, the predicted values, as calculated by the prediction models, are higher than the observations. It is evident that the prediction models overestimate the actual values under all environmental, clothing and metabolic rate combinations by a constant value.

At present, the data collected are analyzed in an attempt to adjust the prediction models for outdoor conditions.

Table 1 - MEAN RECTAL TEMPERATURE ($^{o}$C) AFTER 60 AND 120 MIN. OF EXPOSURE, MEASURED (M) VS. PREDICTED (P) UNDER COASTAL AREA CONDITIONS (30$^{o}$C, 60%RH)

A. Rest (110 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 36.90 | 37.00 | 37.10 | 37.10 |
| | P | 37.57 | 37.38 | 37.98 | 37.64 |
| Sun | M | 37.20 | 37.40 | 37.20 | 37.50 |
| | P | 37.55 | 37.63 | 37.95 | 38.08 |

B. Moderate exercise (320 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 37.60 | 37.90 | 37.60 | 38.00 |
| | P | 37.95 | 38.19 | 38.31 | 38.75 |
| Sun | M | 37.75 | 38.30 | 37.80 | 38.70 |
| | P | 38.26 | 38.50 | 38.90 | 39.43 |

C. Heavy exercise (425 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 37.98 | 38.67 | 38.00 | 38.70 |
| | P | 38.32 | 38.72 | 38.86 | 39.70 |
| Sun | M | 38.19 | 38.82 | 38.15 | - * |
| | P | 38.61 | 39.05 | 39.47 | 40.53 |

* could not be sustained within safty limits.

Table 2 - MEAN RECTAL TEMPERATURE ($^{o}C$) AFTER 60 AND 120 MIN. OF EXPOSURE, MEASURED (M) VS. PREDICTED (P) UNDER DESERT CONDITIONS ($31^{o}C$, 45%RG)

A. Rest (110 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 36.80 | 36.90 | 36.80 | 36.90 |
| | P | 37.18 | 37.32 | 37.29 | 37.52 |
| Sun | M | 37.10 | 37.00 | 37.10 | 37.10 |
| | P | 37.40 | 37.50 | 37.67 | 37.85 |

B. Moderate exercise (320 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 37.30 | 37.30 | 37.40 | 37.50 |
| | P | 37.83 | 38.09 | 38.10 | 38.54 |
| Sun | M | 37.40 | 37.70 | 37.50 | 38.10 |
| | P | 38.07 | 38.34 | 38.53 | 39.05 |

C. Heavy exercise (425 watt)

| | | 60 min. | | 120 min. | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 37.50 | 37.60 | 37.60 | 37.90 |
| | P | 38.14 | 38.46 | 38.53 | 39.11 |
| Sun | M | 37.60 | 38.10 | 37.70 | 38.60 |
| | P | 38.38 | 38.71 | 38.98 | 39.67 |

## Table 3 - SWEAT LOSS ($g\ h^{-1}$) DURING THE EXPOSURE

A. Rest (110 watt)

| | | Desert | | Coast | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 139 | 264 | 200 | 300 |
| | P | 180 | 270 | 180 | 360 |
| Sun | M | 310 | 440 | 460 | 640 |
| | P | 540 | 630 | 760 | 810 |

B. Moderate exercise (320 watt)

| | | Desert | | Coast | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 410 | 560 | 560 | 790 |
| | P | 810 | 1080 | 900 | 1170 |
| Sun | M | 590 | 860 | 760 | 990 |
| | P | 1080 | 1350 | 1260 | 1530 |

C. Heavy exercise (425 watt)

| | | Desert | | Coast | |
|---|---|---|---|---|---|
| | | Fat. | MOPP4 | Fat. | MOPP4 |
| Shade | M | 490 | 750 | 790 | 390 |
| | P | 1080 | 1350 | 1260 | 1620 |
| Sun | M | 680 | 1160 | 960 | 1490(?) |
| | P | 1350 | 1620 | 1530 | 1890 |

(?) see note in table 1C.

Experimental layout for the 2nd phase of the study

The data obtained so far was discussed with the American collaborators from the Military Ergonomics Division at the U.S. Army Research Institute of Environmental Medicine. It was concluded that the study should be continued according to the following guidelines:

1. Metabolic rate: heavy exercise (425 watt)
2. Clothing: standard fatigues
3. Environmental conditions: solar load
   shade

The study will be carried out both indoors and outdoors. Environmental conditions for indoors studies will simulate outdoor conditions concerning ambient temperature and relative humidity. In addition the possibility to validate the prediction models under extremely hot and very dry ambient conditions ( $40^{o}C$, 20% rh) is considered.

This will enable us to investigate the possibility that for outdoor condition a constant correcting factor should be added to the mathematical models. It is hypothesized that this factor might be related to the solar load, which could not be simulated under laboratory conditions.

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